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Recent Progress in the Development of Predictive Capability for Small Fatigue Crack Growth

Chun H. Wang

Defence Science and Technology Organisation,

Melbourne, Australia

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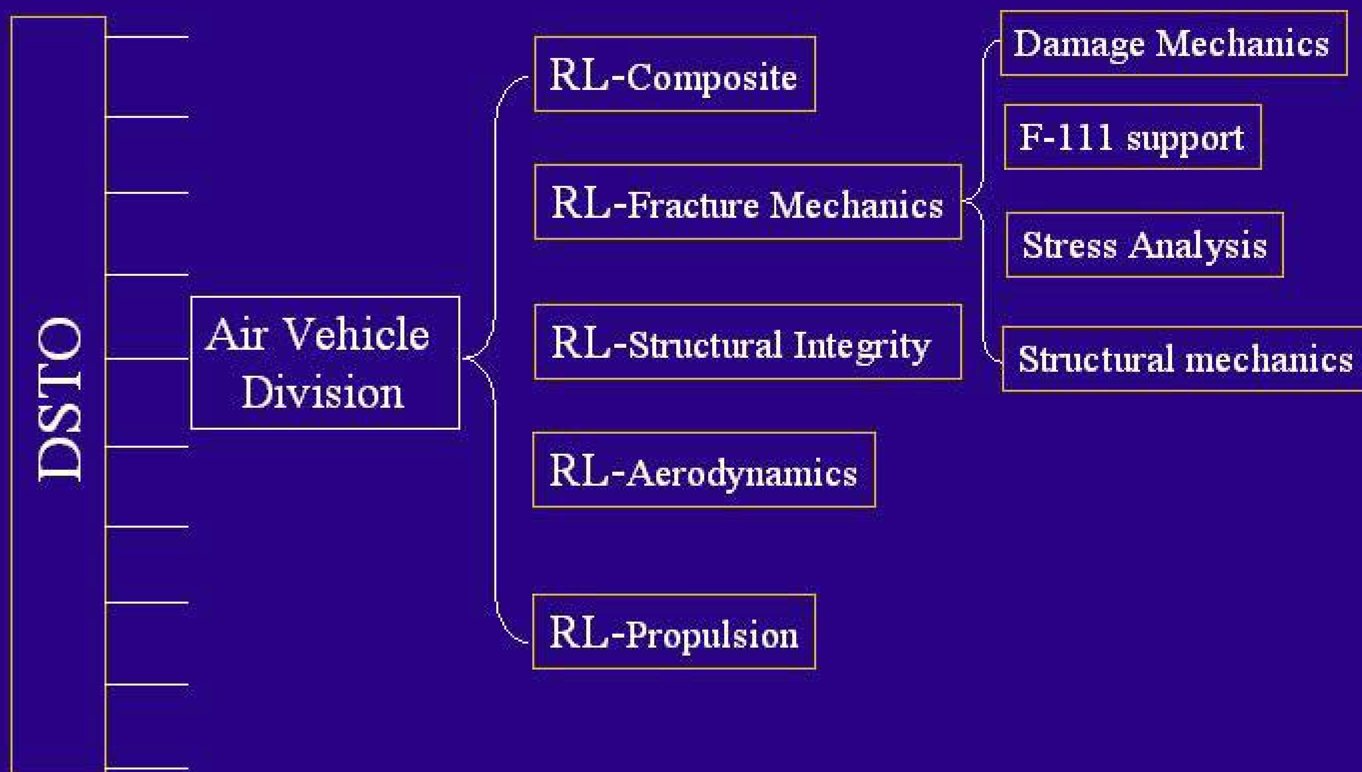

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Overview

- Motivation and Context.
- Some Experimental Observations.
- Theoretical Considerations.
  - Correlating parameter;
  - Plasticity induced crack closure;
- Computational approach.
  - Grossly plastic deformation;
  - Strain gradient (notch plastic zone).
- Applications.
  - Crack growth through residual stress field.
- Conclusions.

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Motivation and Context

Improvement over current engineering practice in life prediction

↓

Prognosis Health Management

Integrated Detection and Assessment

NDI

Fracture / Fatigue Mechanics

Detection
- Find damage
- Locate and identify
- Quantitative characterization, input to Assessment

operator

automation

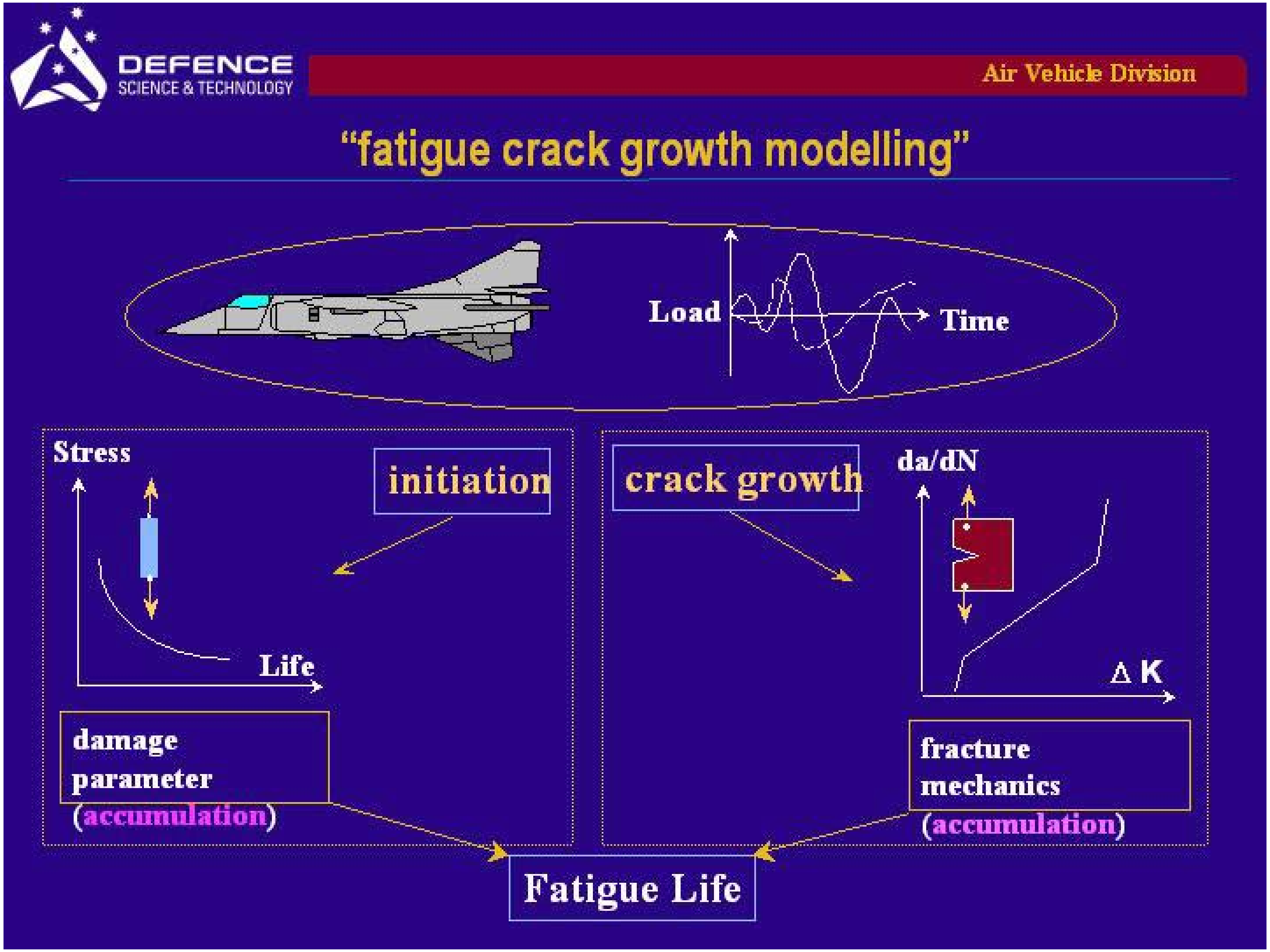
Motivation and Context

A brief history:

1. 1955: First paper on fatigue crack growth using dislocation theory by Dr. Alan Head.
2. 1995: Long crack well understood and predictive tools (FASTRAN by Jim Newman).
3. 2015: Adaptive, 3D computational crack growth?

Challenges:

1. Correlating parameter for small cracks (≥10 μm).
2. Crack closure (plasticity and surface roughness induced).
3. Scale effect (crack size relative to microstructure dimension).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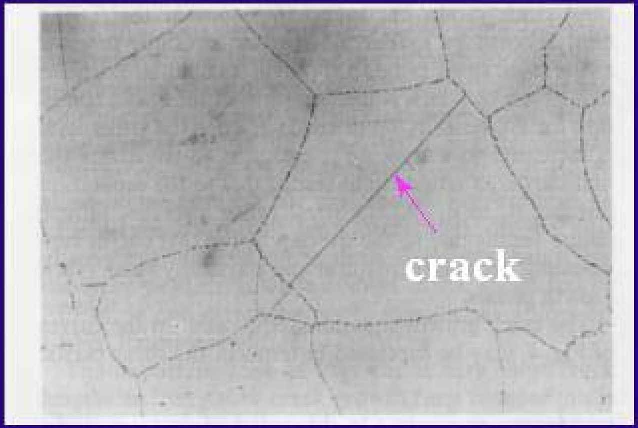
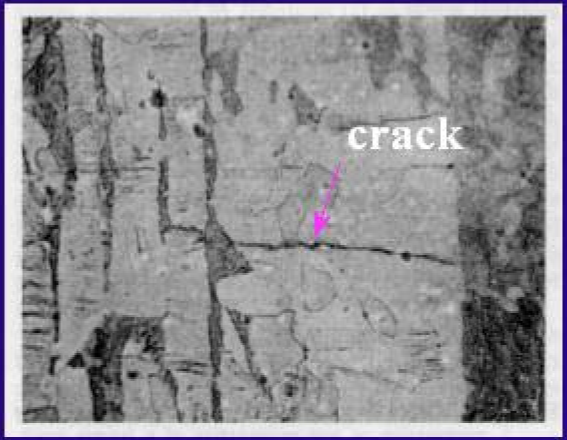
"fatigue crack growth modelling"
Load
Time
Stress
initiation
Life
damage
parameter
(accumulation)
crack growth
da/dN
Δ K
fracture
mechanics
(accumulation)
Fatigue Life

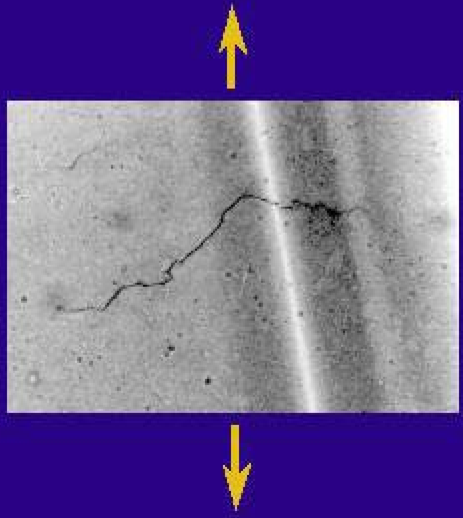
Some Experimental Observations



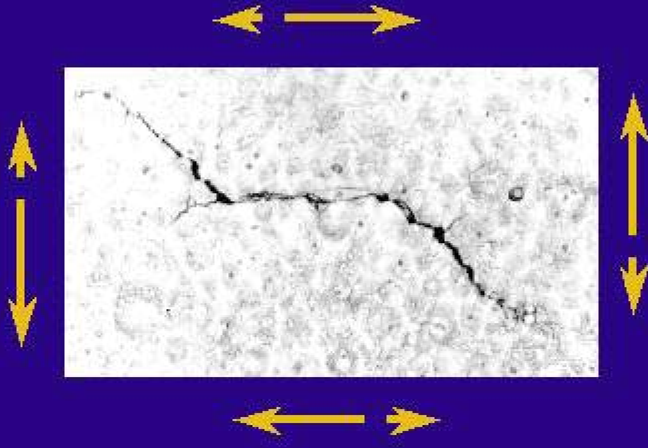


Some Experimental Observations

tension



torsion



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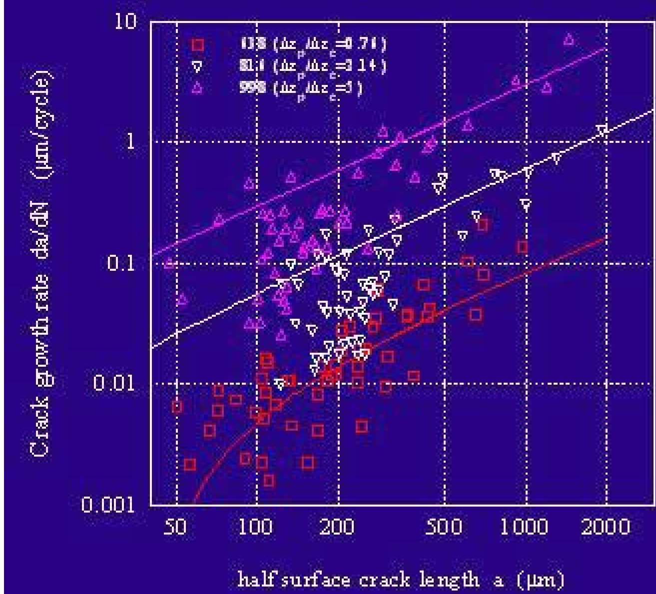
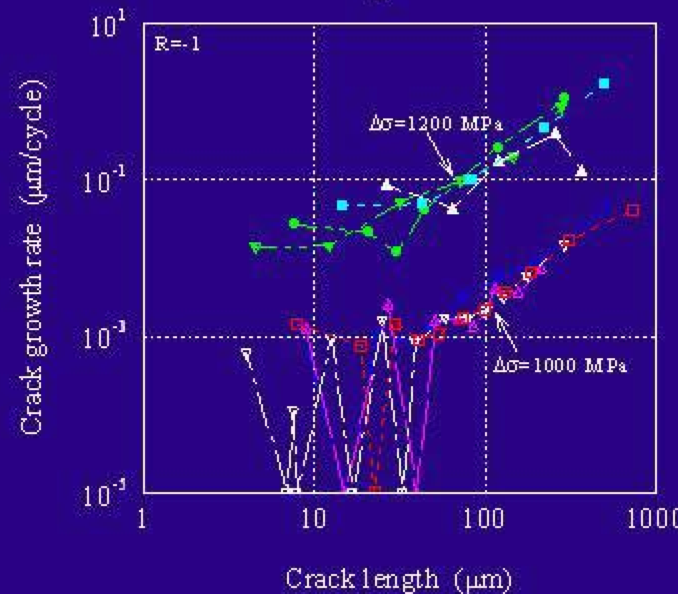
Some Experimental Observations

Mild carbon steel

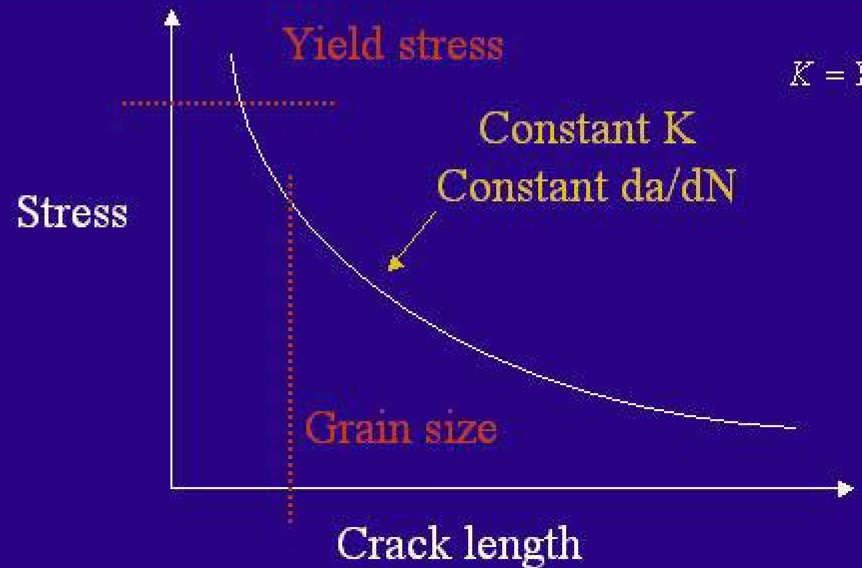


Alloy



Failure of Stress Intensity Factor to Correlate Crack Growth Rates

Correlating Parameter



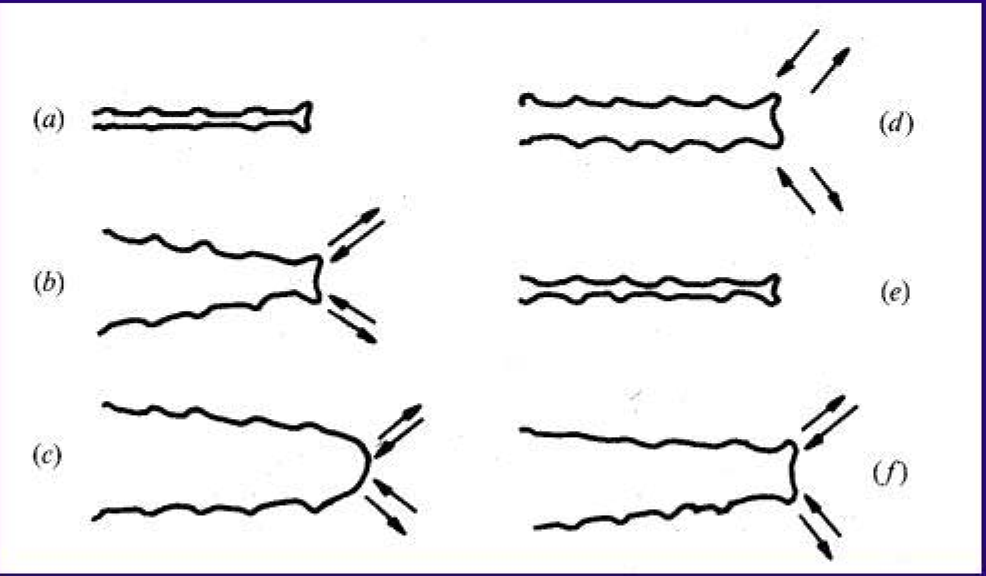
$$K = Y\sigma\sqrt{\pi a}$$

(i) Failure of similitude

(ii) Failure of continuum hypothesis

Correlating Parameter

Stage II growth by plastic blunting at crack tip (Laird, 1967)



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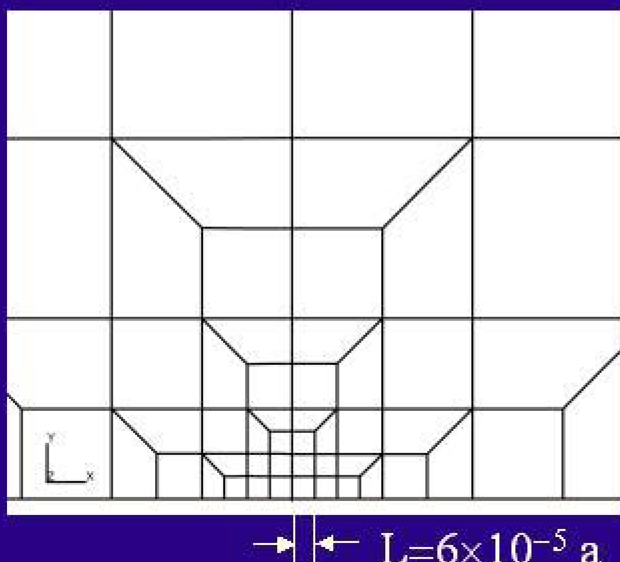
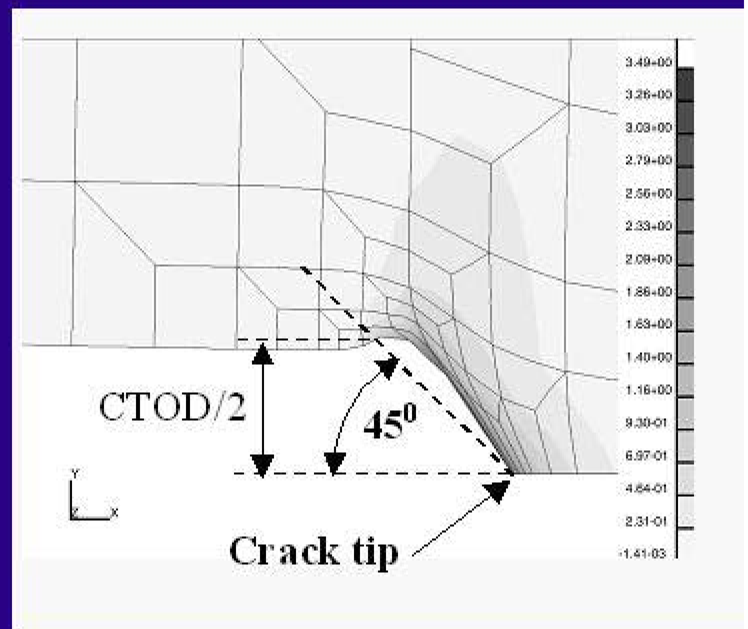
Correlating Parameter for Small Cracks

Un-deformed geometry

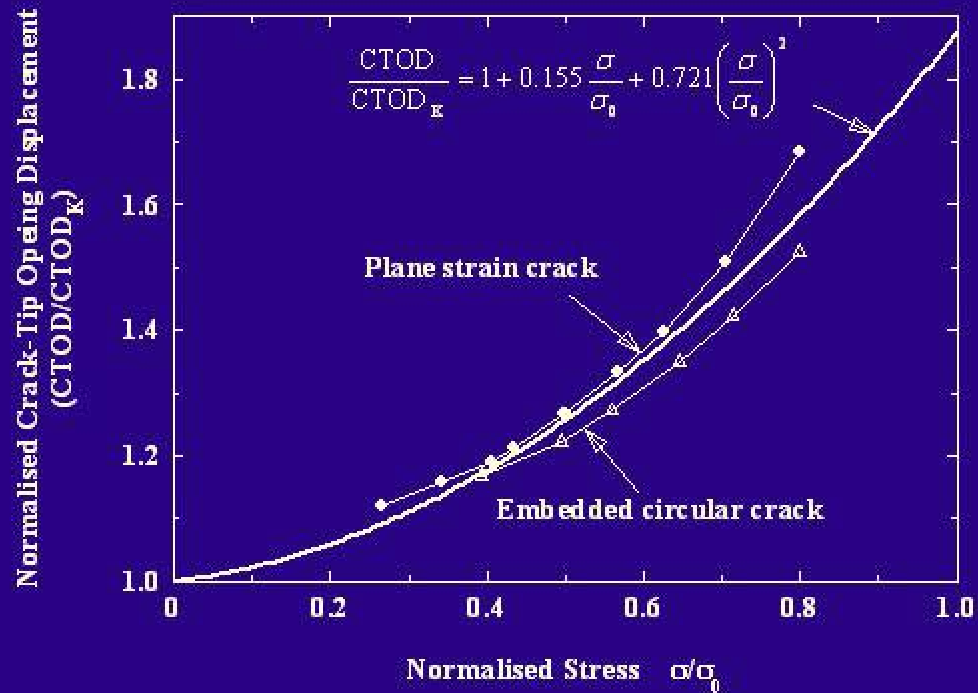


Deformed geometry



Correlating Parameter for Small Cracks

Cyclic Crack-tip Plastic Bunting



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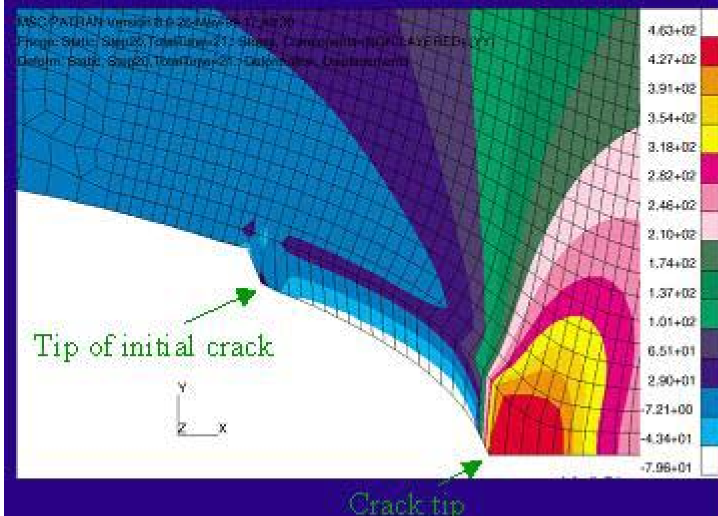
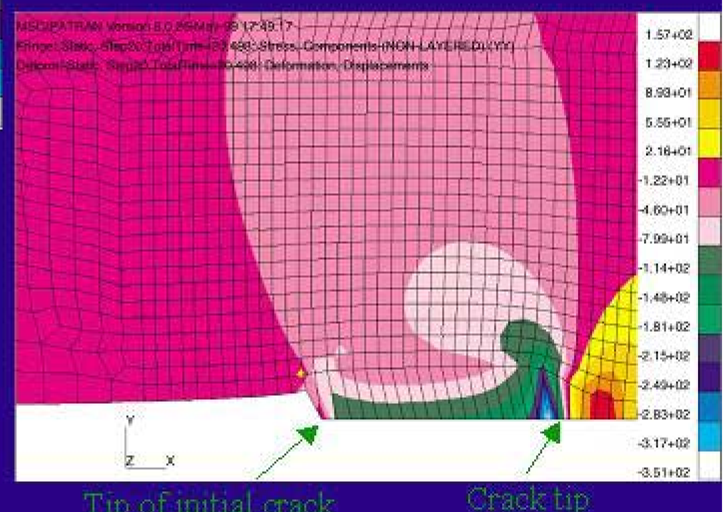
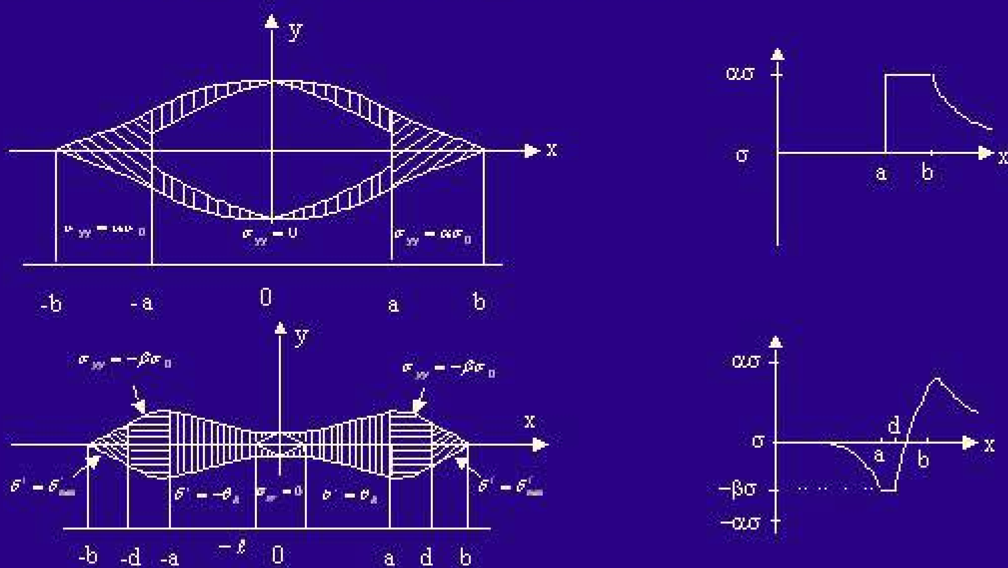
Crack Closure under Cyclic Loading





Modified Crack Closure Solution

- Simulating three-dimensional plastic deformation near crack tip using two-dimensional Dugdale model.
- Two plastic constraint factors.



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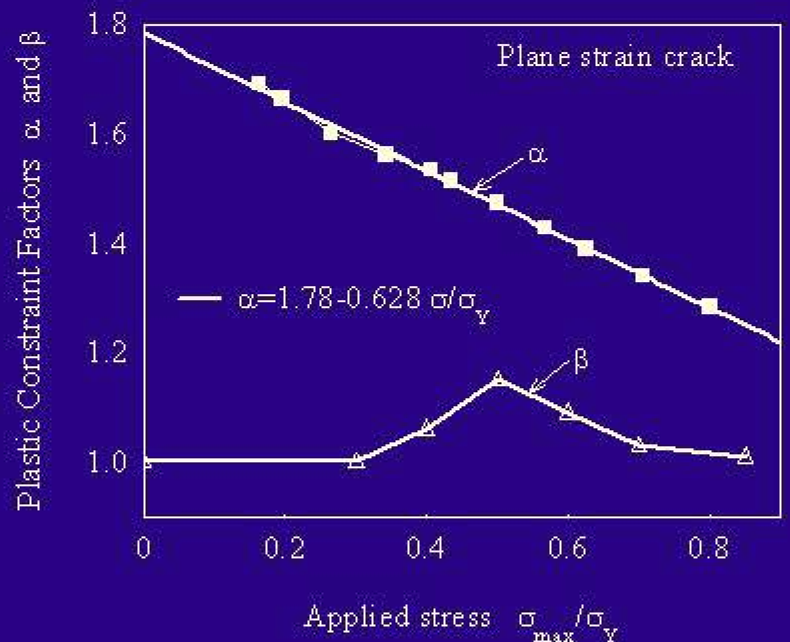
Modified Crack Closure Solution

- Two plastic constraint factors: determined by matching analytical and FE solutions.
- Input to modified FASTRAN for spectrum loading.



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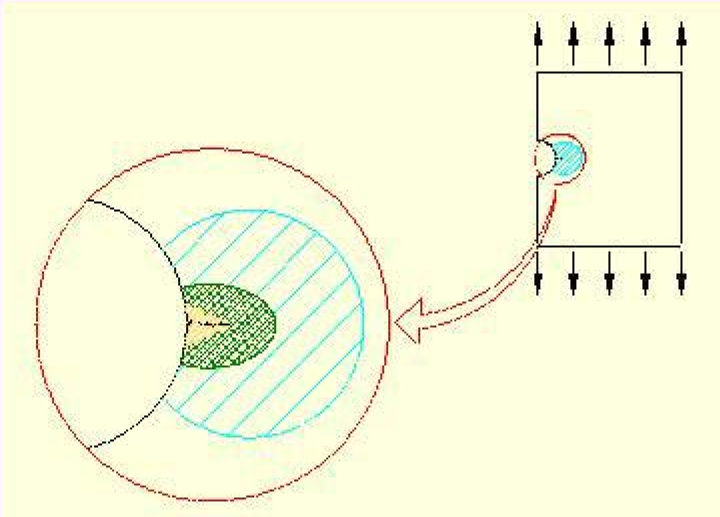
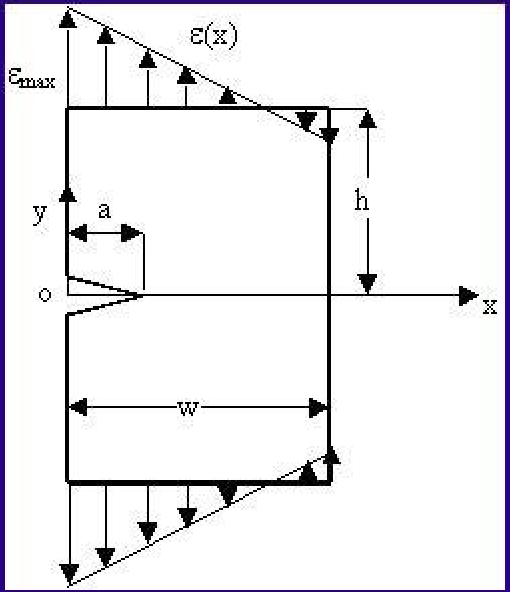
Strain Gradient Effect

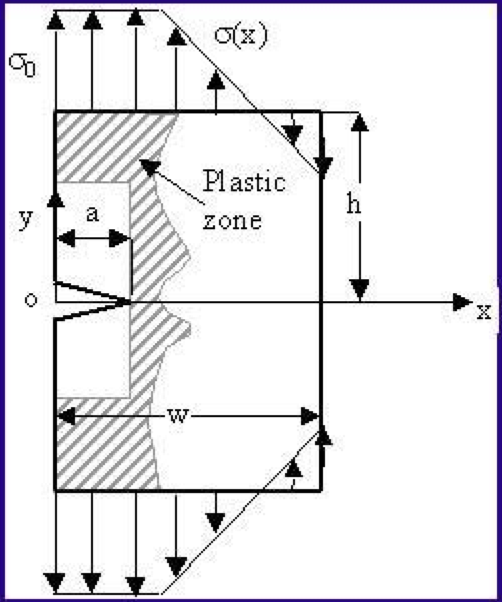
- Small crack emanating from notch plastic zone
  - Cyclic Notch Plasticity
  - Small Cracks
    - Non-SSY
    - Plastic Strain Controlled
    - Microstructure



Strain Gradient Effect



Applied Strain



Elasto-plastic Stress

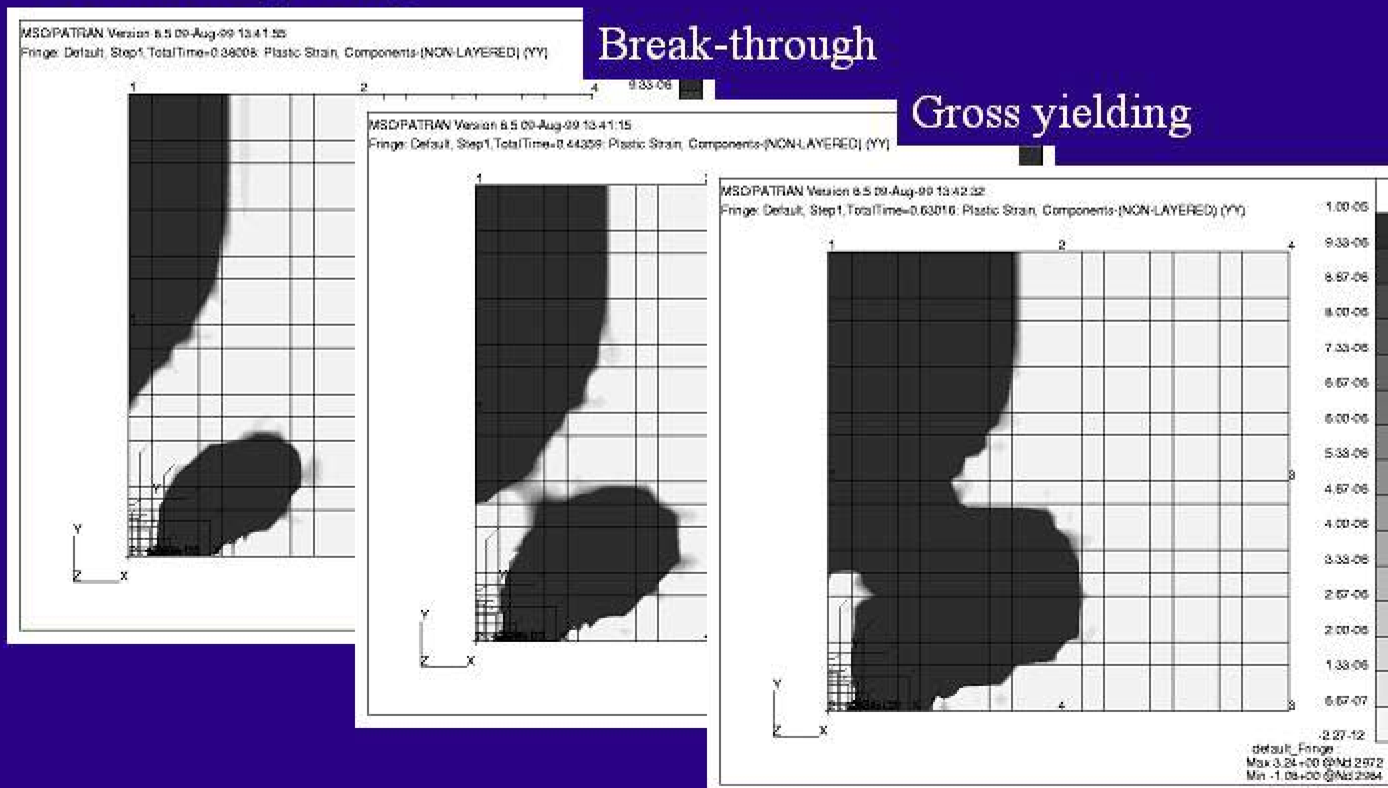
Stress-based Dugdale Models I & II

Strain Gradient Effect

Front face yielding

Break-through

Gross yielding



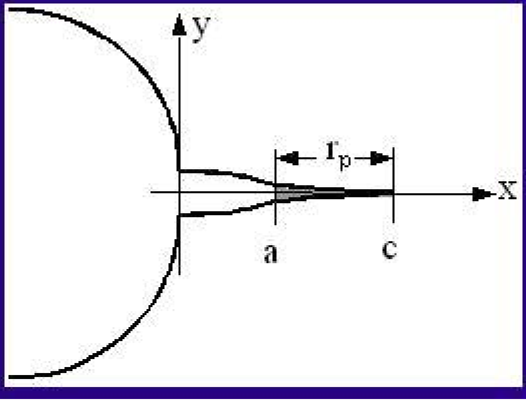
Strain Gradient Effect

Strain-based Dugdale Model

$$\int_0^{c_3} D(t)Q(x,t)dt = \begin{cases} -\sigma_{yy}(x)/E' & (0<x<a) \\ [-\sigma_{yy}(x)+\sigma_0]/E' & (a<x<c_3) \end{cases}$$

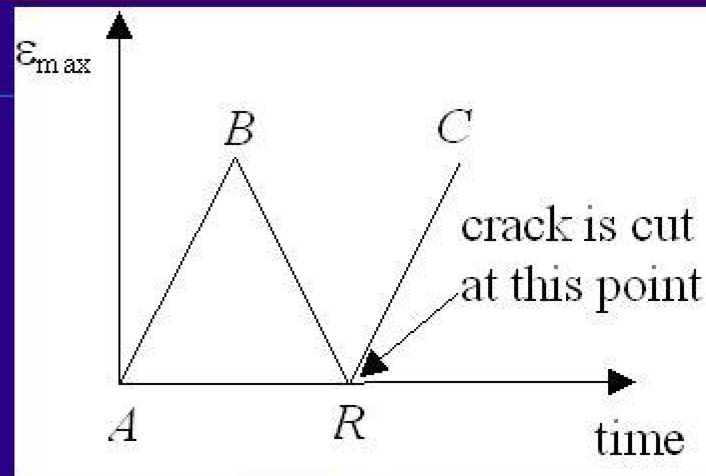
$$\int_0^{c_3} D(t)Q(x,t)dt = \begin{cases} -\varepsilon_{ep}(x) & (0<x<a) \\ -\varepsilon_{ep}(x)+\sigma_0/E_s(x) & (a<x<c_3) \end{cases}$$

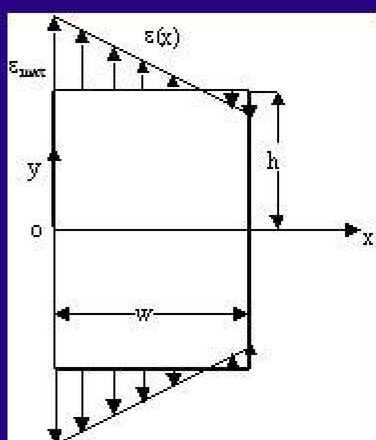
$$E_s(x) = \sigma_{ep}(x)/\varepsilon_{ep}(x)$$

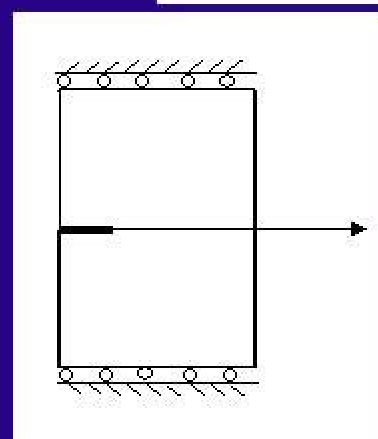


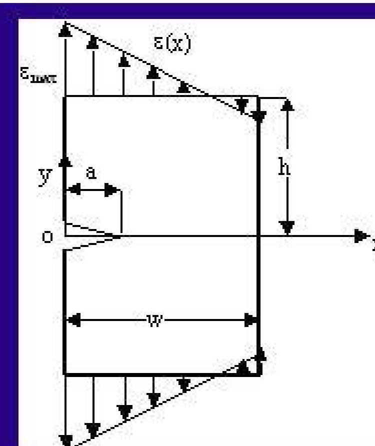
Strain Gradient Effect

Load history of pre-straining









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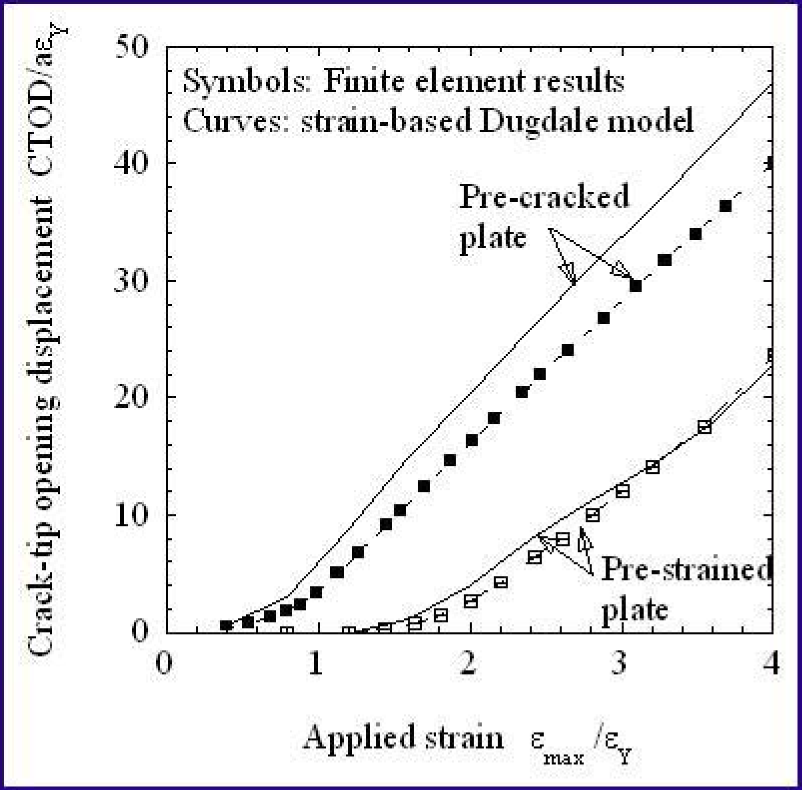
Strain Gradient Effect



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Crack Growth Through Residual Stress Field

Surface enhancement techniques

- Shot peening
- Laser shock
- Low plasticity burnishing

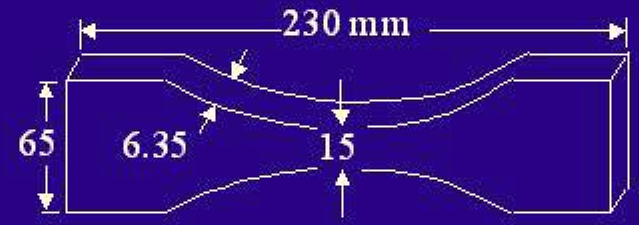
No credit is taken of the benefit of residual stresses

- Quality assurance.
- Stability of residual stresses under mechanical or thermal loading.
- Fatigue crack growth: influence of flaws.

Experiments

Aluminum alloy (7050)

- Etched
- Shot peened



Loading

- FALSTAFF
- Modified sequence representative of F/A-18

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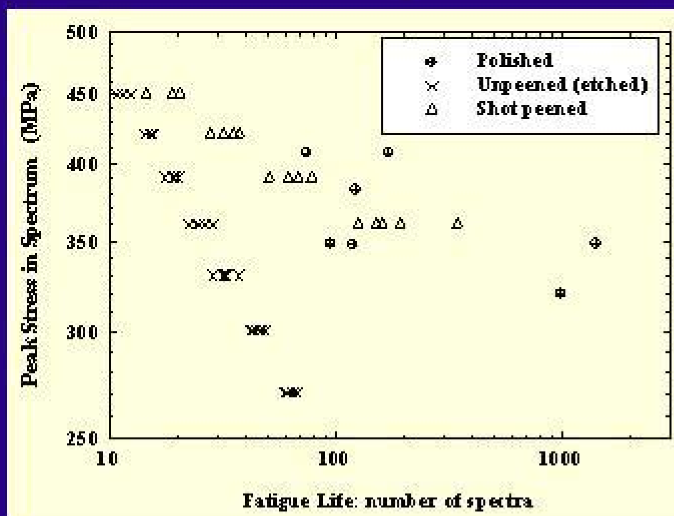
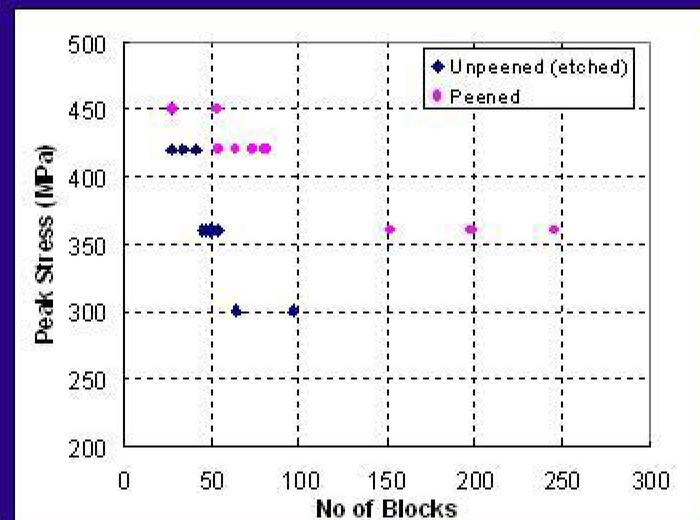
Experimental Results

F/A-18 sequence



FALSTAFF



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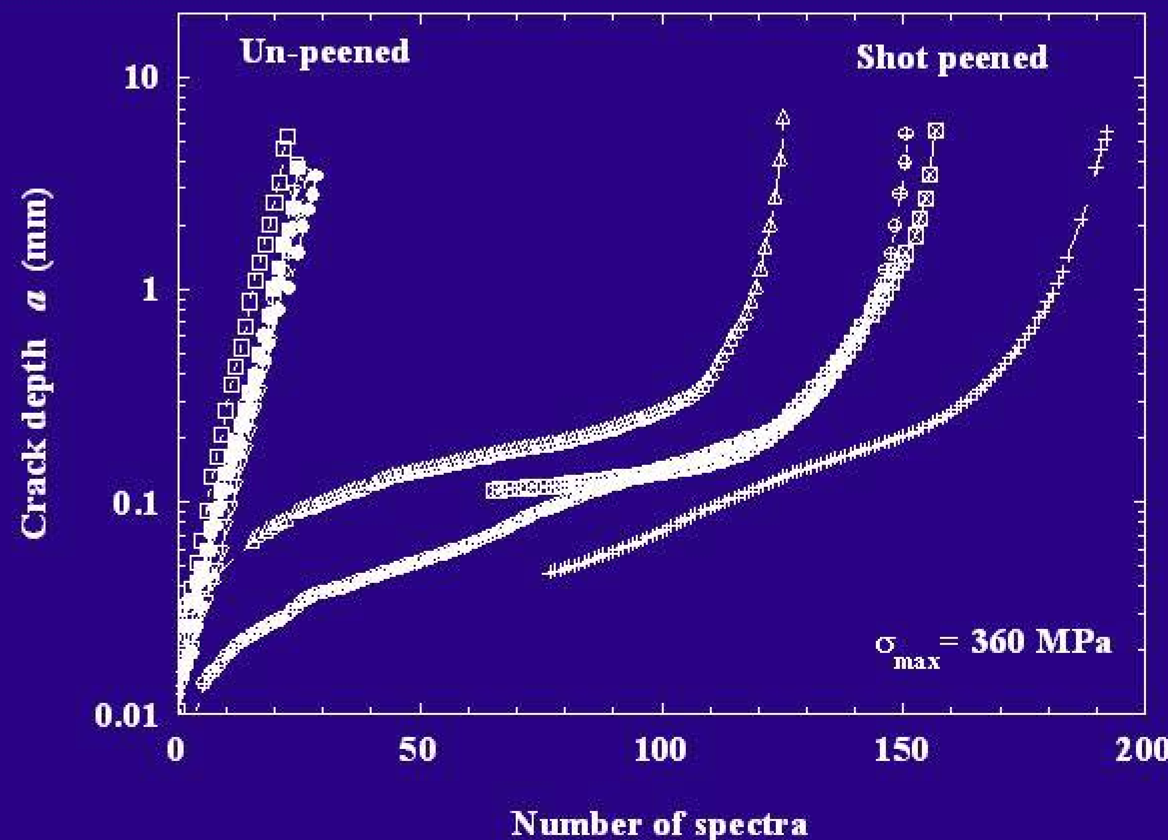
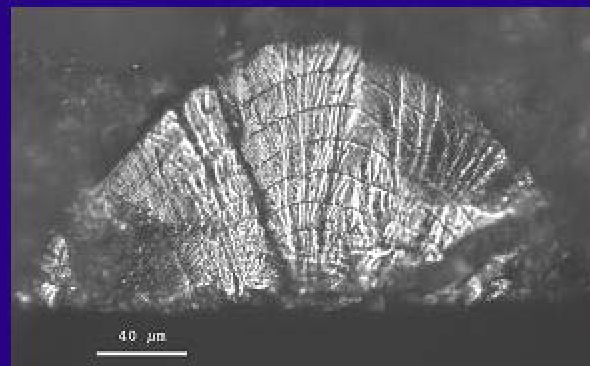
Crack Growth Results

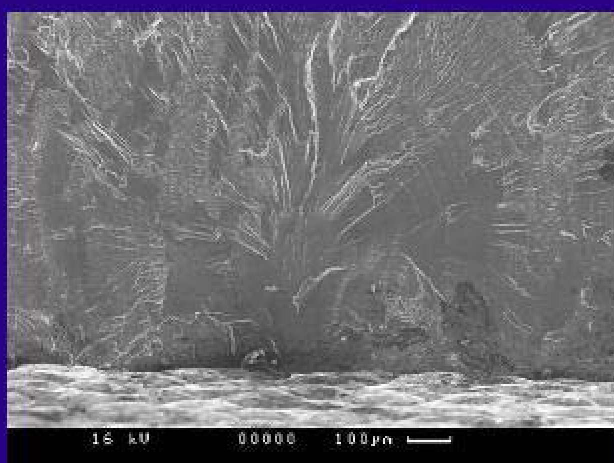


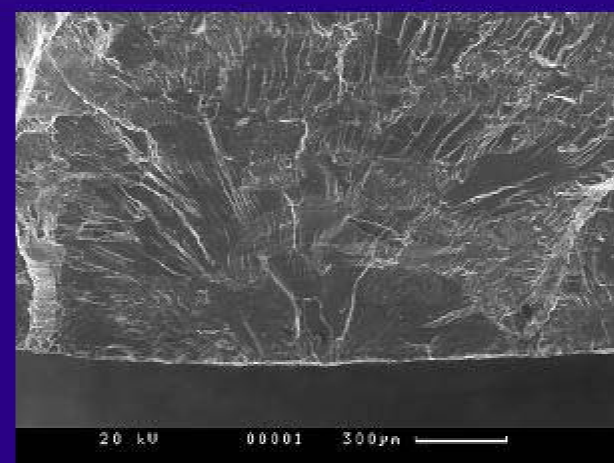
Fractographic Results



Un-peened

Shot peened

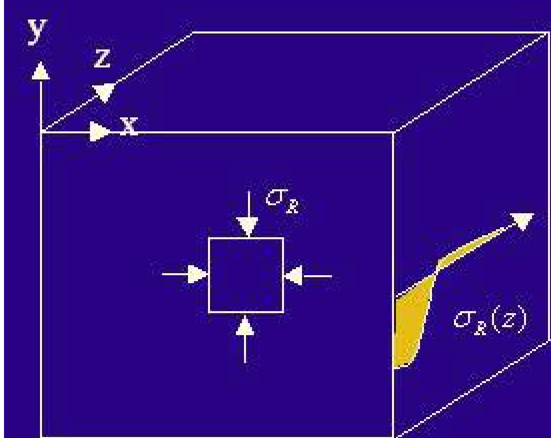


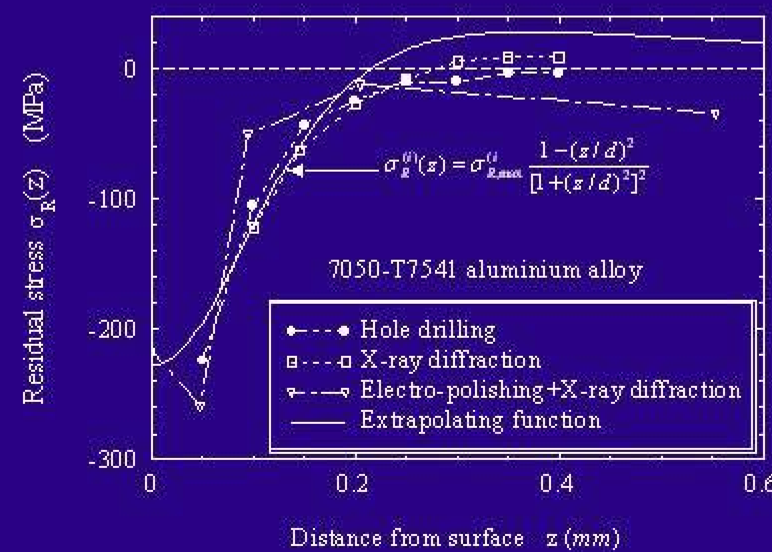


Fatigue Crack Growth Prediction

- Correlating parameter;
  - Cyclic crack-tip opening displacement.
- Cycle-by-cycle crack closure analysis;
  - Effect of residual stress.
  - Modified Dugdale model (e.g., FASTRAN).
- Material database;
  - da/dN .vs. correlating parameter (threshold for small cracks).
- Initial flaw size;
  - Fractographic analysis.

RESIDUAL STRESS

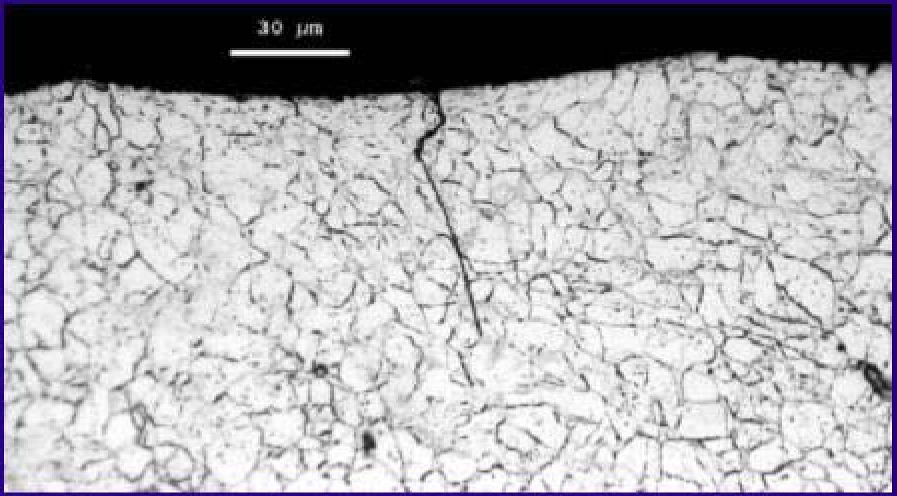




$$\sigma_R^{(i)}(z) = \sigma_{R\max}^{(i)} \frac{1-(z/d)^2}{[1+(z/d)^2]^2}$$

$$\int_0^{\infty} \sigma_R^{(i)}(z)dz = 0$$

Initial Flaws due to Shot Peening



Stability of Residual Stresses

Stress shake-down:

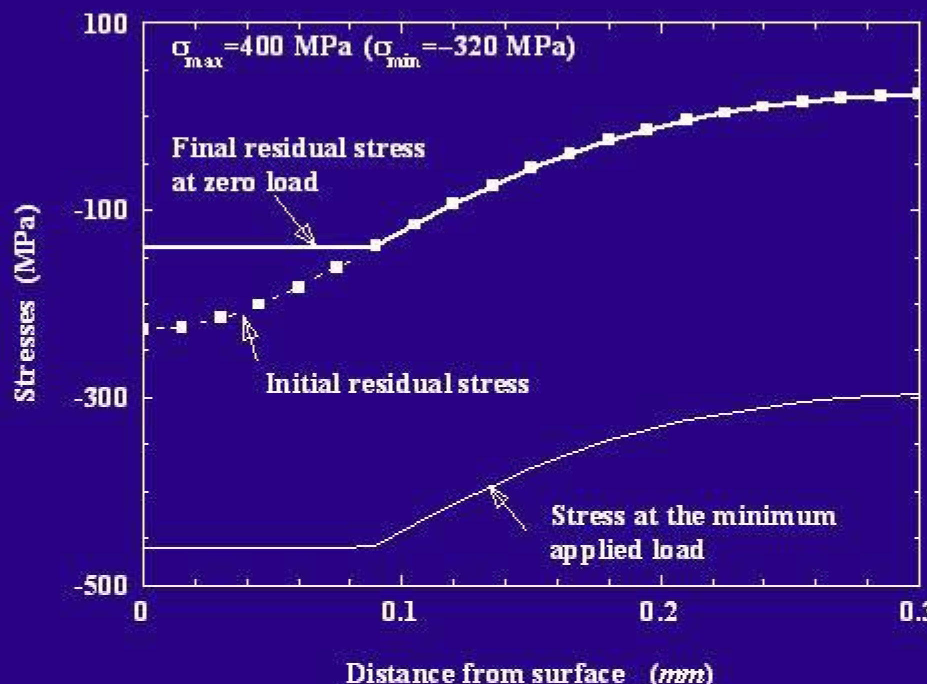
- Elastic shake-down: zero alternating plasticity.
- Plastic shake-down: alternating plasticity (zero mean stress).

Compressive residual stress

- High compressive load may cause elastic or plastic shake-down.
- Rate of shake-down depends on material properties and applied loads.

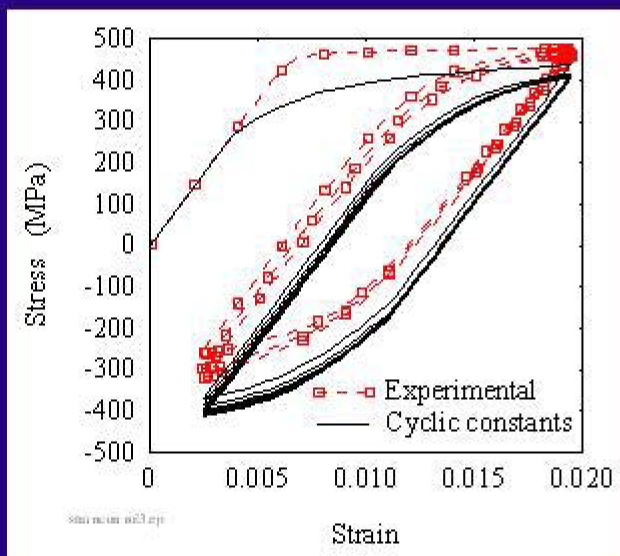
Relaxation of Residual Stress

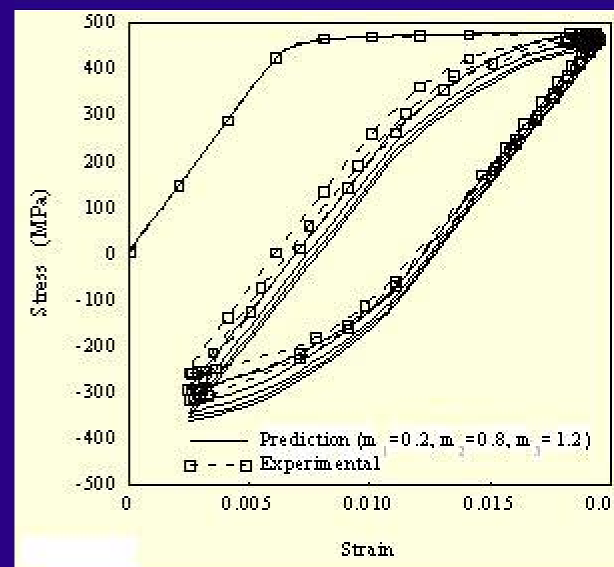
Perfectly plastic material



Cyclic Deformation

7050 Aluminium





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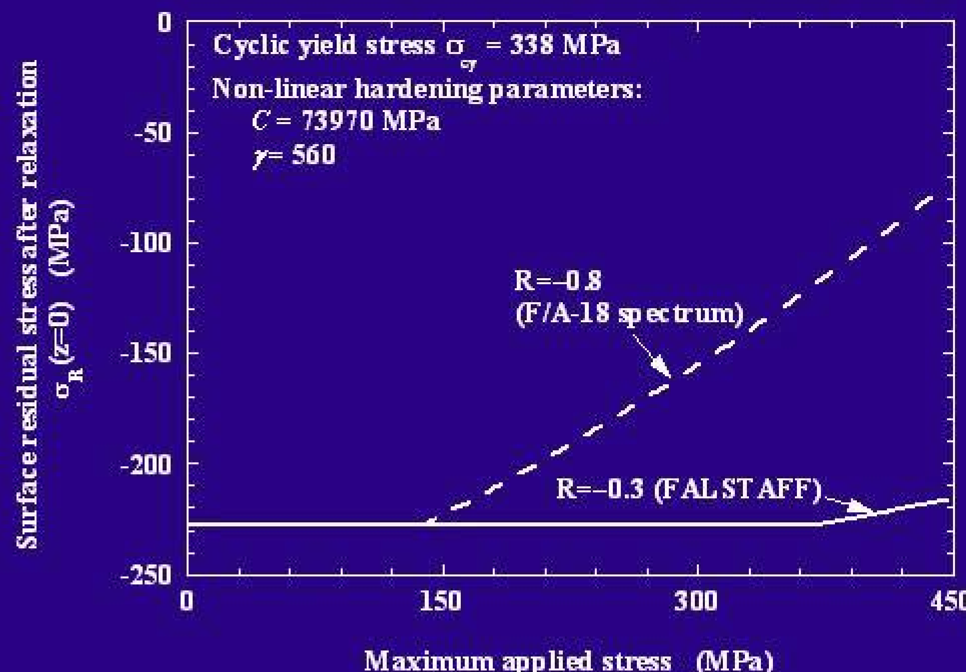
Relaxation of Residual Stress

Non-linear
Kinematic hardening



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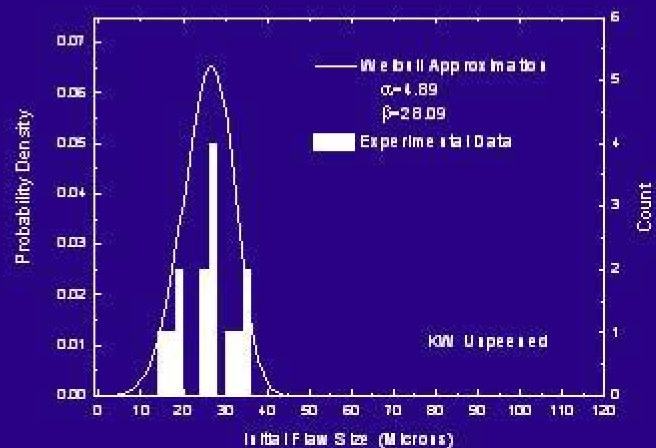
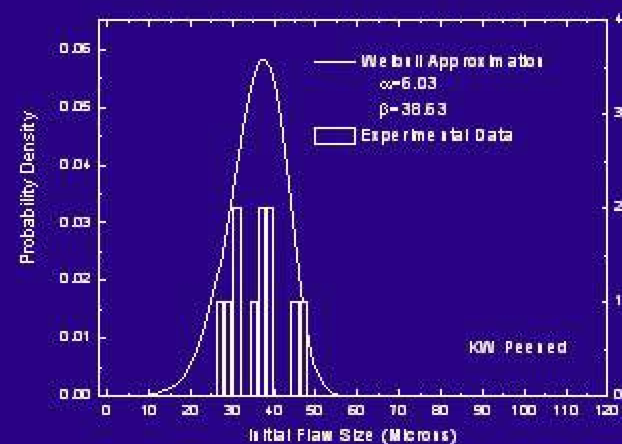
Distribution of Initial Flaws





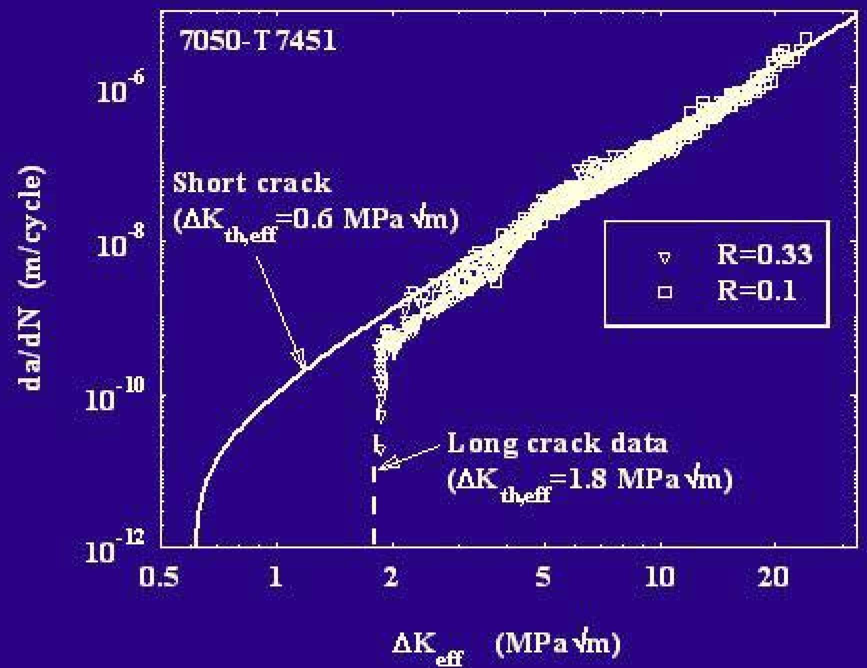
Material Database

Threshold value is determined so that the initial flaw does not propagate at fatigue limit.

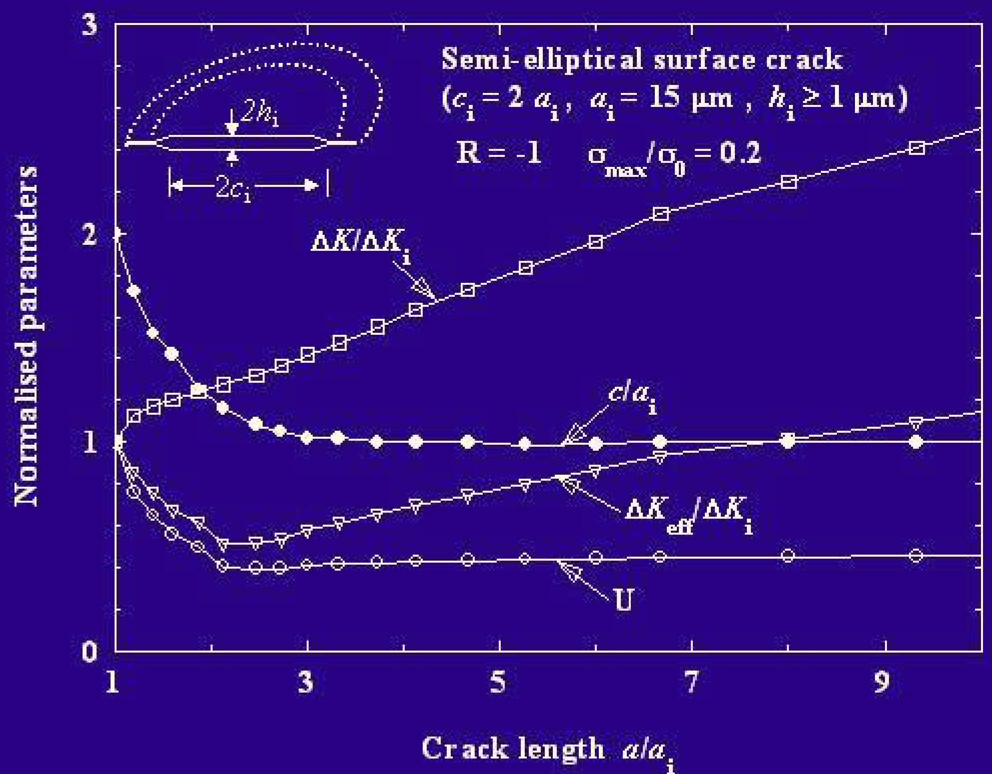
Input:

(1) Flaw size

(2) Fatigue limit



Threshold Determination

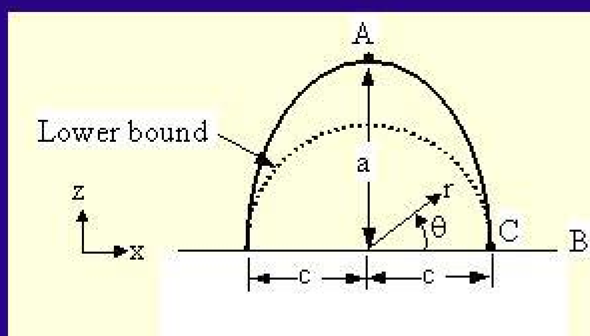


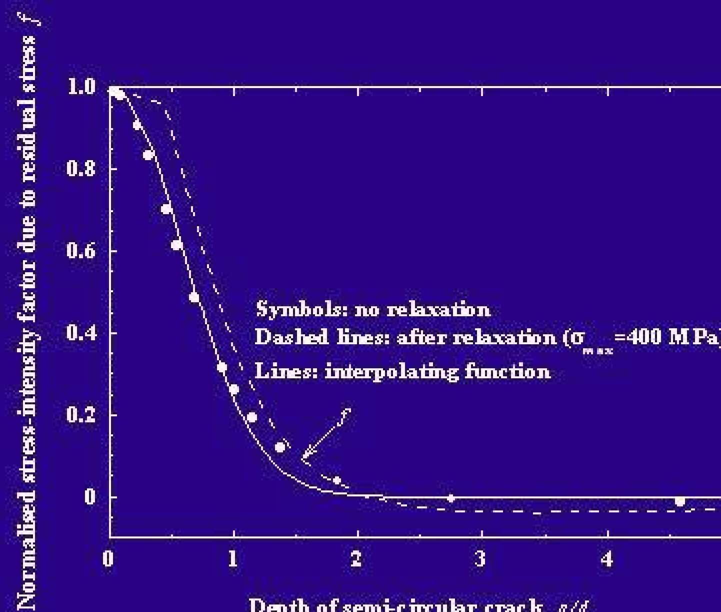
Influence of Residual Stress on Crack Growth

$$K^R = \int_0^a \int_0^\pi \sigma_R (r \sin\theta) G(r,\theta) r\,d\theta\,dr$$

$$G(r,\theta) = \frac{\sqrt{a^2 - r^2}}{\pi\sqrt{\pi a}} \left[\frac{1}{a^2 + r^2 - 2ar\sin\theta} + \frac{1}{a^2 + r^2 + 2ar\sin\theta} \right]$$

$$f = \frac{K^R}{2\sigma_{R,\max}\sqrt{a/\pi}}$$





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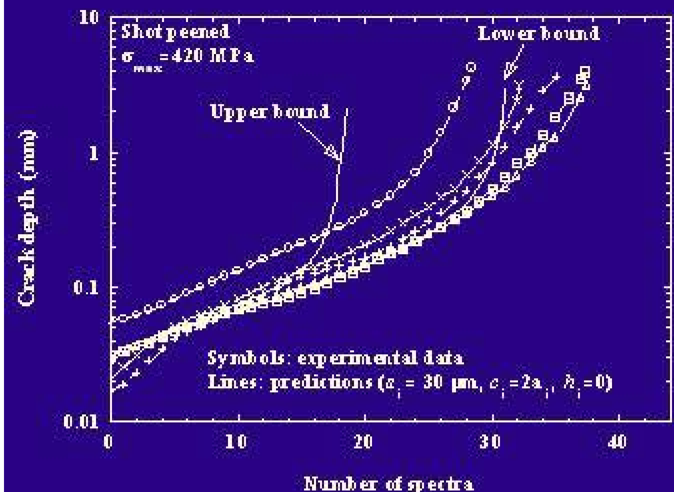
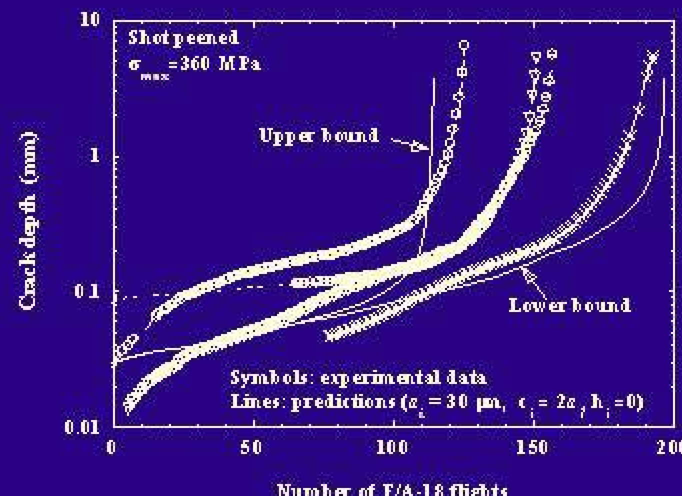
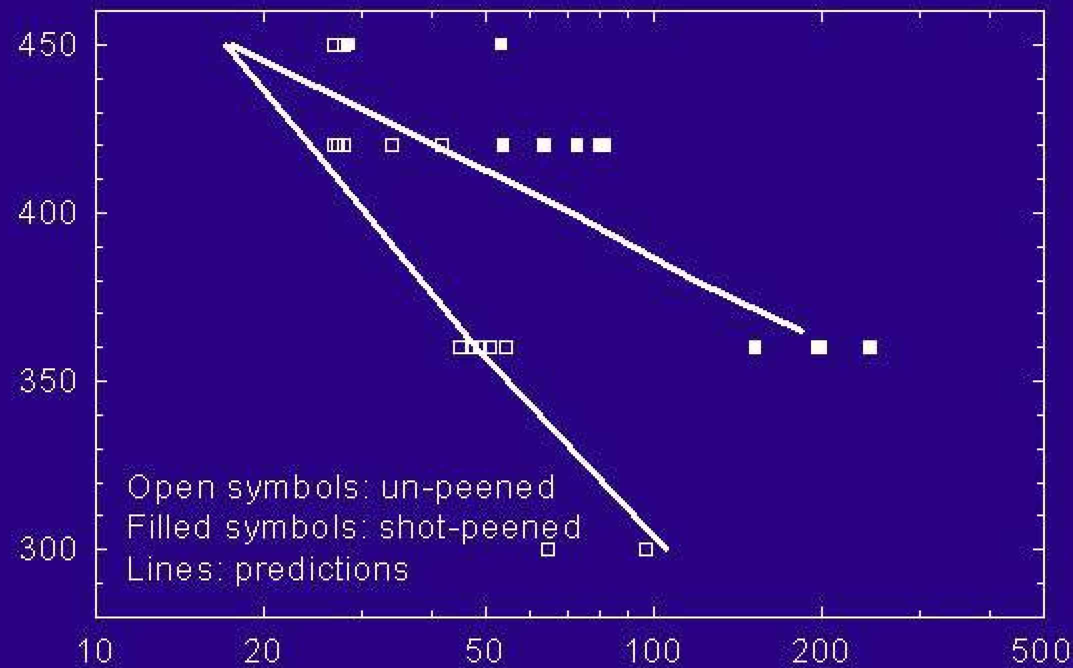
Crack Growth Curves





Comparison of Prediction with Experimental Data



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Summary

- Correlating parameter for short crack growth.
- Strain-based cohesive zone model for strain-controlled crack growth at notch root.
- Modified crack closure model for large-scale yielding.
- Analytical method for characterizing the relaxation rate and the final distribution of residual stresses.
- Predictive tools for assessing effect of surface enhancement.